EFFECT OF HEAT TREATMENT ON WEAR PROPERTIES OF PLAIN CARBON STEEL

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology

In

Metallurgical & Materials engineering

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2013

NATIONAL INSTITUTE OF TECHNOLOGY ROURKELA

CERTIFICATE

This is to certify that the thesis entitled "Effect of heat treatment on wear properties of plain carbon steel" submitted by Tusharkanta Daspattanayak (109MM0439) and Kaibalya Mohanty (109MM0118) in partial fulfilments for the requirements for the award of Bachelor of Technology Degree in Metallurgical and Materials engineering, at National Institute of Technology Rourkela, is an authentic work carried out by them under my supervision and guidance.

To the best of my knowledge, the matters embodied in the thesis have not been submitted to any other university/institute for the award of any degree or diploma.

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ACKNOWLEDGEMENT

We wish to express our deep sense of gratitude to Prof. A. Basu, our guide, for his consistent encouragement, guidance and support to carry out and complete this project, and for giving us an opportunity to work on this project.

We are sincerely grateful to Prof. B.C Ray, Head of the Department of Metallurgical and Materials Engineering, NIT-Rourkela, for providing all the necessary facilities in the department.

We would like to express our deep sense of gratitude to Prof S.K Pratihar, Head of the Department of Ceramic Engineering, for his timely help and support.

We would be highly obliged to extend our thanks to Mr. Uday Kumar Sahu and Mr. Rajesh Patnaik, and Mr. Hembram for their immense support and help rendered while carrying out our experiments, without which the completion of this project would have been at stake.

We would also like to thank all the staff members of MME Dept., NITR and everyone who in some way or the other has provided us valuable guidance, suggestion and help for this project.

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Abstract

A study was made of the effect of heat treatment upon the wear resistance of low and high carbon steels as determined by the ball on a plate wear-testing machine (diamond indenter) under combined action of rolling and sliding friction under pressures. Total ten samples of the steel (5 samples each from low carbon and high carbon range) were subjected to five different heat treatments i.e. annealing, normalizing, oil quenching, water delay quenching and water quenching heated to a temperature of 960˚C. One from each heat treated types was prepared for microstructural and hardness studies. The hardness of the five different heat treated samples was measured by Vickers hardness testing machine. Optical microscopies to study the microstructure and Scanning electron microscopic analysis of wear surface have been done.

Annealed steels gave inferior wear-resisting qualities. Normalized steel showed less wear resistance in the low-carbon range than the annealed steel, but in the high-carbon range approached the relatively high wear resistance of the delay hardened steels. Hardened steels (water quenched and oil quenched) showed a very rapid increase in wear resistance with increased carbon content. The water delay quenched steel showed lesser wear resistance as compared to oil quenched samples though the hardness of former is more than the latter.

The scanning electron microscopy images of wear surfaces of steels showed that this particular type of wear (combined rolling and sliding friction under pressures) was generally accompanied by severe distortion of the structure and the images demonstrated exactly what was interpreted from wear-testing results.

A martensitic micro structure was the most favorable for resisting wear of the type studied. Properly normalized high-carbon steels, which showed a structure of lamellar pearlite, had almost as good wear resistance as the delay hardened steels. Annealed high-carbon steels, showing a structure predominately spheroidized cementite, had relatively poor resistance to wear. Apparently free ferrite or free cementite (as spheroids) is detrimental to the resistance to wear.

Keywords*:* plain carbon steel, wear depth, sliding distance, penetration rate, delay quenching

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1. Introduction

Steel, in modern age, has found a vast application in almost every field. India's 33 per cent growth in steel production in the last five years was second only to China among the top-five producing nations. Steels represent the most important group of engineering materials as they have the widest diversity of applications of any of the engineering materials. Generally, carbon is the most important element profoundly affecting the mechanical properties of the steels. Increasing the carbon content of steels increases the hardness and strength. More-over, plain carbon steels have moderate strengths and can resist satisfactorily ordinary temperatures and atmospheres and also are available in large quantities, in quite large variations of shapes and sizes with a much lower cost.

In their service periods, steels parts undergo heavy working stresses. As a result wearing and tearing take place in the body parts. The quality of the steel products depends on the condition of their surfaces and on surface deterioration due to use. Surface deterioration is also important in engineering practice; it is often the major factor limiting the life and performance of machine components. Wear may be defined as the unintentional deterioration resulting from use or environment. It may be considered essentially a surface phenomenon. Wear is one of the most destructive influences to which metal are exposed, and the importance of wear resistance needs no amplification. The displacement and detachment of metallic particles from a metallic surface may be caused by contact with (1) another metal (adhesive or metallic wear), (2) a metallic or a nonmetallic abrasive (abrasion), or (3) moving liquids or gases (erosion). The above three types of wears may be subdivided into wear under rolling friction or sliding friction and, further, according to whether lubrication can or can't be used [1].

Different heat treatment processes are adopted for achieving improved mechanical properties like hardness, ductility; wear resistance etc. studies reveal that steels having higher hardness values show a better resistance to wear. This is in accordance with Archard's equation i.e.

$$Q = KWL / H$$

Where, Q= total volume of wear debris produced, W= total normal load, L= sliding distance and H= hardness of softest contacting surface.

2. Literature survey

A STEEL is usually defined as an alloy of iron and carbon with the carbon content between a few hundreds of a percent up to about 2 wt.%. Other alloying elements can amount in total to about 5 wt. % in low-alloy steels and higher in more highly alloyed steels such as tool steels and stainless steels. Steels can exhibit a wide variety of properties depending on composition as well as the phases and micro constituents present, which in turn depend on the heat treatment [3].

2.1 The Fe-C Phase Diagram

The basis for the understanding of the heat treatment of steels is the Fe-C phase diagram (Fig. 1). Figure 1 actually shows two diagrams; the stable iron-graphite diagram (dashed lines) and the metastable Fe-Fe_3C diagram. The stable condition usually takes a very long time to develop, especially in the low-temperature and low-carbon range, and therefore the metastable diagram is of more interest. The Fe-C diagram shows which phases are to be expected at equilibrium (or metastable equilibrium) for different combinations of carbon concentration and temperature. We distinguish at the low-carbon end ferrite (α-iron), which can at most dissolve 0.028 wt.% C at 727°C and austenite (γ-iron), which can dissolve 2.11 wt.% C at 1148 °C . At the carbon-rich side we find cementite (Fe_3C) of less interest, except for highly alloyed steels, is the δ-ferrite existing at the highest temperatures [2].

Between the single-phase fields are found regions with mixtures of two phases, such as ferrite + cementite, austenite + cementite, and ferrite + austenite. At the highest temperatures, the liquid phase field can be found and below this are the two phase fields liquid + austenite, liquid + cementite, and liquid + δ-ferrite.Some important boundaries at single-phase fields include: A_1, the so-called eutectoid temperature, which is the minimum temperature for austeniteA3, the lower-temperature boundary of the austenite region at low carbon contents, that is, the γ/γ + α boundary· A_{cm}, the counterpart boundary for high carbon contents, that is, the γ/γ + Fe_3C boundary. If alloying elements are added to the iron-carbon alloy (steel), the position of the A_1, A_3, and A_{cm} boundaries and the eutectoid composition are changed [2].

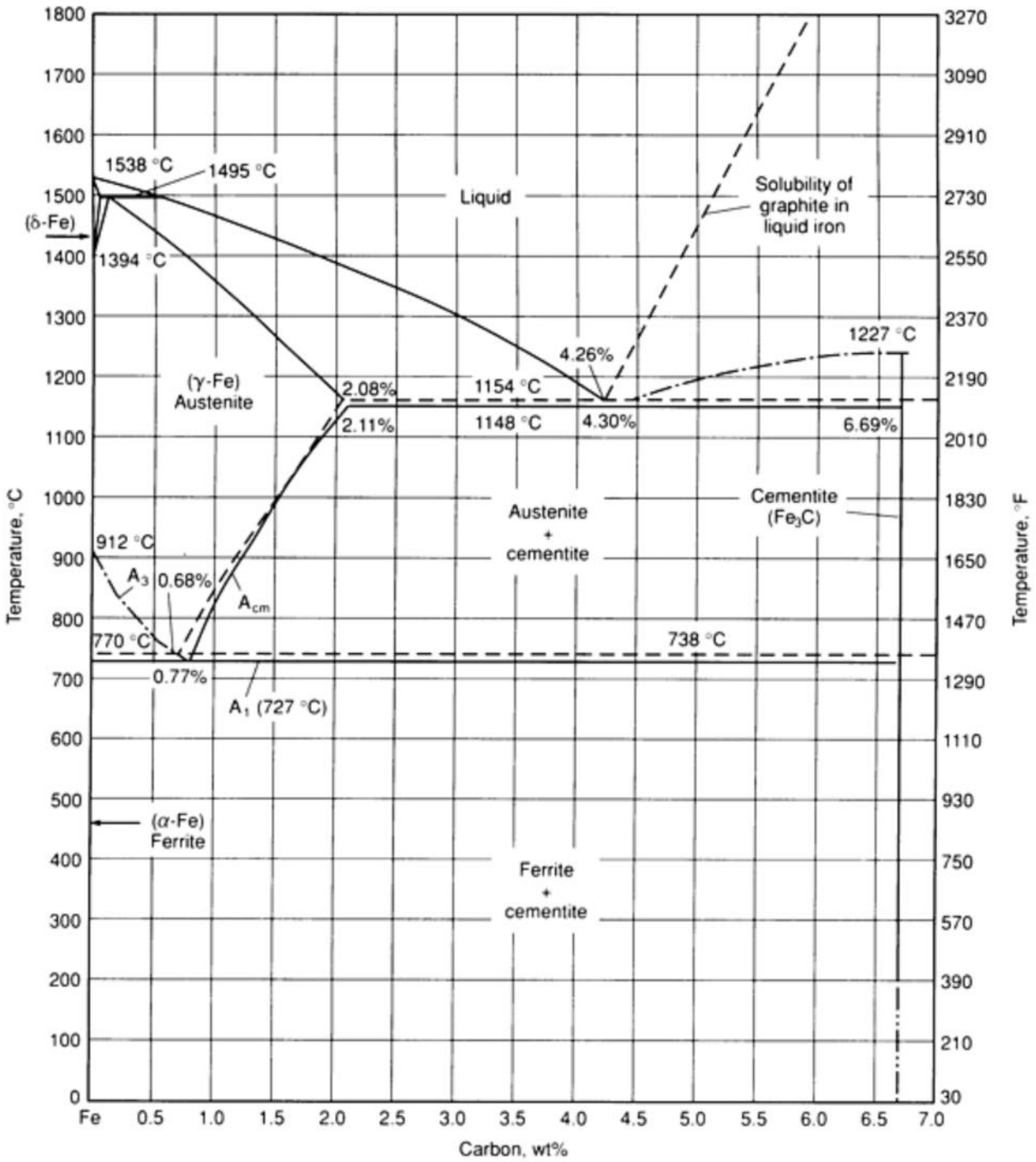


Fig. 2.1 The Fe-C equilibrium diagram up to 6.67 wt. % C. Solid lines indicate Fe-Fe_3C diagram; dashed lines indicate iron-graphite diagram [2].

2.2 Principle of heat treatment

A combination of heating, soaking and cooling operationstimed and applied to a metal, or alloy in the solid state in a way that will produce desired properties. These properties are dependent on microstructure of the alloy, i.e. the nature, shape, size, distribution and amount of phases, which are controlled by changes in the alloy constituents, and mainly by heat treatment. Different heat treatments bring about a very wide range and distribution of phases [3].

A heat treatment process consists of:

(1) Heating the steel to a high predetermined temperature, called austenitization temperature.
(2) Soaking for some period of time to obtain a homogeneous austenite throughout the cross section of the steel part.
(3) Cooling to room temperature at a particular cooling rate which depends on the properties to be developed in the steel.

There are different kinds of heat treatment processes. The most common ones are:

(1) Annealing

(2) Normalizing

(3) Quenching

2.2.1 Annealing

ANNEALING is a generic term denoting a treatment that consists of heating to and holding at a suitable temperature followed by cooling at an appropriate rate(normally very slow cooling), primarily for the softening of metallic materials [2]. Generally, in plain carbon steels, annealing produces a ferrite-pearlite microstructure. Annealing of a metal is performed generally for the following purposes [9]:

- Removal of internal stresses
- Homogenization of structure
- facilitate cold working or machining
- improve mechanical or electrical properties
- promote dimensional stability

In this project, we have adopted full annealing operation i.e. heating the steel to a temperature above the upper critical temperature, soaking there for sufficient time to obtain homogeneous austenite and then cooled in the furnace by switching it off. The austenitizing temperature for full annealing is a function of carbon content of the steel. The relation is as follows:

For hypo eutectoid/eutectoid steels:

A.T= A_3 + (20-40° C)

For hypereutectoid steel:

A.T= A_1 + (20-40° C)

Where, A.T= austenitizing temperature

A_1= lower critical temperature

A_3= upper critical temperature

Three important factors that should be taken into prior consideration during full annealing are:

- proper austenitizing temperature
- soaking time
- very slow cooling through A_1

2.2.2 Normalizing

Normalizing is the process ofheating the steel above the upper critical temperature to attain homogeneous single phase austenitic region, soaking at that temperature for a particular period of time and allowing to cool freely in air. Typically, the work is heated to a temperature above the upper critical line of the iron-iron carbide phase diagram, that is, above A_3 for hypo eutectoid steels and above Acm for hypereutectoid steels. The austenitic temperature ranges for steels depending on the carbon content are as follows:

$T_{normalizing}$ = { A_3 + (40-60° C) for hypo eutectoid/eutectoid steels ; A_{cm} + (30-50° C) for hypereutectoid steels

Normalizing operation of steel is performed to achieve the following objectives:

- to refine the coarse grains of the steel castings
- to improve mechanical properties of plain carbon steel
- to eliminate or reduce microstructural irregularities
- to increase machinability of low carbon steels
- to eliminate or break coarse cementite network in hypereutectoid steels
- general refinement of structure prior to quenching operation

It differs from annealing in two important process variables:

- Higher austenitizing temperature than annealing to attain more homogenization, so that it could be super cooled much below A_1 temperature before transformation takes place [3].

- Air cooling being faster than furnace cooling helps austenite supercool much below A_1 temperature before transformation occurs.

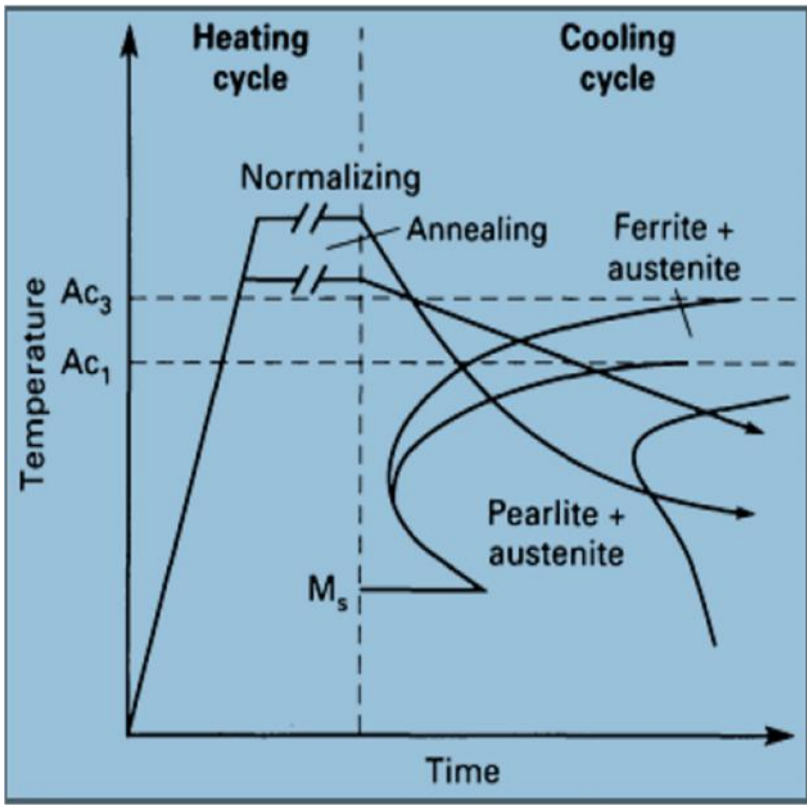


Fig.2.2 Schematic illustration of process of normalizing and annealing[2]

The resulting microstructure of normalizing operation consists of:

- Finer proeutectoid ferrite grains
- Much finer perlite
- Low amount of proeutectoid ferrite than that in annealed structure.

2.2.3 Quenching

It is the process of heating the steel to proper austenitizing temperature, soaking at this temperature to get a fine grained and homogeneous austenite, and then cooling the steel at a rate faster than its critical cooling rate. Parent austenite thus transforms into martensite and the steel becomes very hard.Successful quenching/hardening usually means achieving the required

microstructure, hardness, strength, or toughness while minimizing residual stress, distortion, and the possibility of cracking.

The selection of a quenchant medium depends on the hardenability of the particular alloy, the section thickness and shape involved, and the cooling rates needed to achieve the desired microstructure. The most common quenchant media are either liquids or gases. The liquid quenchants commonly used include:

- Oil that may contain a variety of additives
- Water
- Aqueous polymer solutions
- Water that may contain salt or caustic additives
- Gaseous quenchants like helium, argon, and nitrogen.(These quenchants are sometimes used after austenitizing in a vacuum.)

Quenching is performed for achieving following objectives:

- Main aim of hardening tools is to induce high hardness and subsequently improve their cutting ability.
- Most of the machine parts and all the tools are hardened to improve their wear resistance.
- The main objective of hardening machine components made of structural steels is to develop high yield strength with good toughness and ductility to bear higher working stresses.
- Stainless and high-alloy steels may be
- Quenched to minimize the presence of grain boundary carbides or to improve the ferrite distribution [3].

The austenitizing temperature of plain carbon steels depends on the carbon content of the steel and is generalized as:

$T_{quenching} = A_3 + (20\text{-}40^{\circ}C)$ for hypoeutectoid steels

$A_1 + (20\text{-}40^{\circ}C)$ for hypereutectoid/eutectoid steels

2.2.4 Delay quenching (Special heat treatment process)

Delay quenching though is not a standard and required heat treatment process in industry but can be useful to study the TTT diagram and effect of any accidental possible delay in actual practice.

Austenitized steel is taken out of the hardening salt bath held for some time so as to make the temperature fall, and then quenched in suitable medium. This operation results in minimum distortion as the temperature of quenching is low. High speed steels and case hardening steels are often given this treatment.

2.3 Wear

Wear is erosion or sideways displacement of material from its "derivative" and original position on a solid surfaceperformed by the action of another surface.Wear is related to interactions between surfaces and more specifically the removal and deformation of material on a surface as a result of mechanical action of the opposite surface. The need for relative motion between two surfaces and initial mechanical contact between asperities is an important distinction between mechanical wear compared to other processes with similar outcomes.The definition of wear may include loss of dimension from plastic deformation if it is originated at the interface between two slidingsurfaces.

2.3.1 Different types of wear

2.3.1.1 Abrasive wear

It involves ploughing of localized surface contacts through a softer mated material [5]. Non-metallic particles usually cause abrasion but metallic particles can also cause abrasion. A material is seriously abraded or scratched if the particle is harder than itself. Abrasive wear can be divided into three different types: low stress (Fig. 2.3(a)), high stress (Fig. 2.3(b)) and gouging (Fig. 2.3(c)). Low-stress abrasion or scratching can be defined as wear that involves a relatively light rubbing contact of abrasive particles with the metal. The subsurface deformation is minimal and shows scratches, hence the surface does not work harden.

High stress abrasion involves wear under stress, high enough to crush the abrasive and hence more strain hardening occurs. Examples are abrasion by rolling-contact bearings, gears, cams and pivots. Gouging abrasion is the high-stress abrasion that results in sizable grooves or gouges on the worn surface. In this type of wear, strain hardening and deformation are the

dominant factors. This form of wear occurs on parts of crusher liners, impact hammers in pulverizers, etc.

Factors affecting abrasion resistance are: microstructure, hardness, and carbon content (for steel), e.g. for low stress abrasion, hard martensitic structure is preferable. Martensitic stainless steel is used for its high hardness where high-stress abrasion occurs.

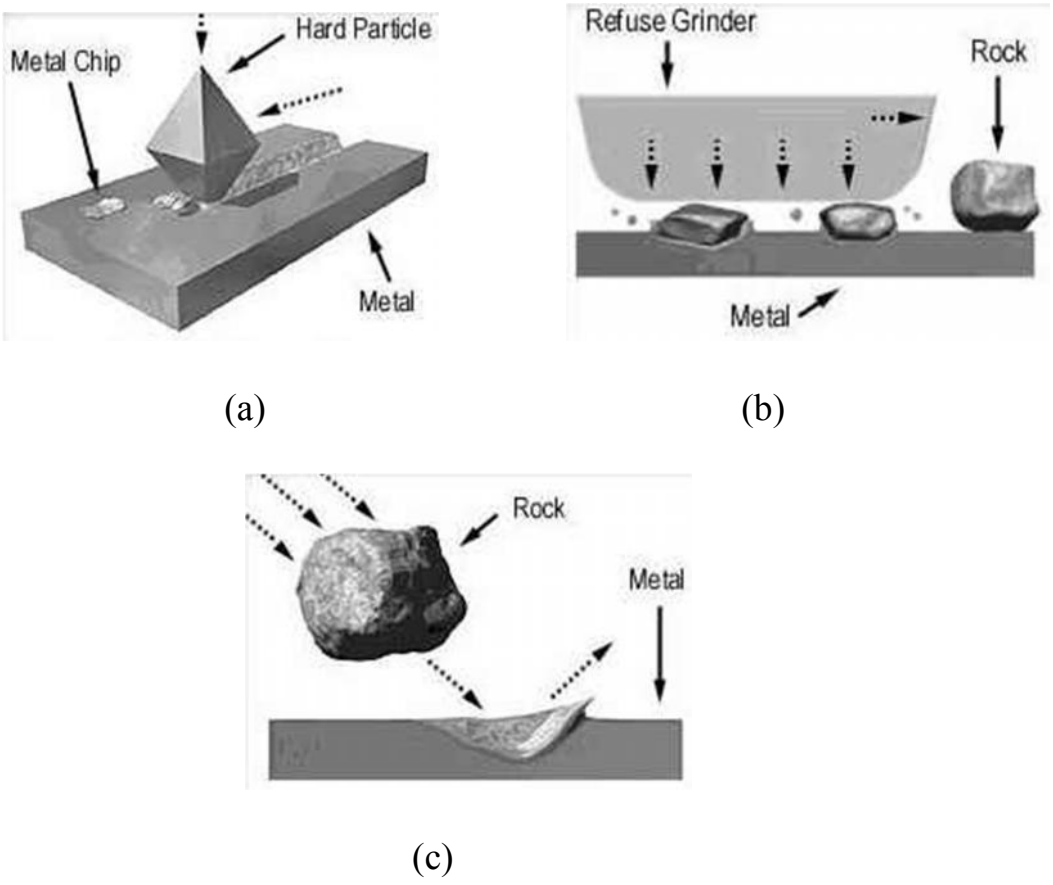


Fig. 2.3 (a) Low stress abrasive wear, (b) high stress abrasive wear, (c) gouging

2.3.1.2 Fretting wear

The process involves wear caused by the small amplitude vibrations (Fig. 2.4) at mechanical connections e.g. at riveted joints [5].This is caused by the combined effects of oxidation and abrasive wear. Two oscillating metallic surfaces produce tiny metallic fragments that oxidize and become abrasive. Subsequently, wear progresses by mild adhesive wear in combination with abrasive wear. Factors that influence fretting wear are contact conditions, environmental conditions and material properties. Fretting is influenced by parameters such as load frequency, amplitude of fretting motion, numbers of fretting cycles, relative humidity and temperature [4].

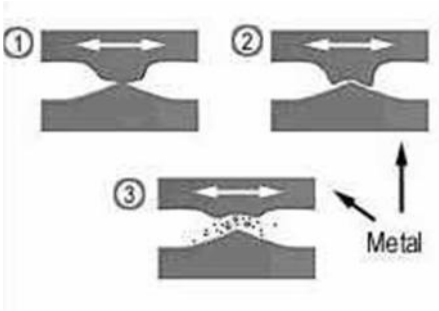


Fig. 2.4 Schematic representation of fretting wear

2.3.1.3 Corrosive wear

It involves wear under the influence of corrosive reagent [5]. Corrosion is the process of electrochemical removal of material form surface by dissolution whereas wear involves the removal of material due to physical interaction between the two surfaces. These two processes affect synergistically to accelerate the materials removal from its surface and termed as corrosive wear. This type of wear involves the disruption and removal of the oxide film, leading to exposure of active metal surface to the environment, dissolution or re-passivation of the exposed metal surface, elastic field interaction at asperities in contact with the environment and the interaction between the plastically deformed areas and its environment. In mining industries, abrasive wear is aggravated by a wet corrosive environment. Carbon steel readily forms iron

oxide, which is removed by sliding and bumping of moving coal/ore causing continuous loss of metal thickness. Stainless steel for its resistance to removal of oxide layer on its surface is desirable for the application in corrosive wear environment.

2.3.1.4 Fatigue wear or contact fatigue

It occurs when a surface is stressed in a cyclic manner (Fig. 2.5). This type of wear can be found in parts subjected to rolling contact, such as ball bearings and gears. Surface conditions, such as finish, residual stress, hardness and microstructure play a role in determining the extent of fatigue wear. Surface treatments e.g. nitriding, carburizing and shot peening which increase surface hardness and improve residual stress distribution in turn could enhance resistance to fatigue wear [5].

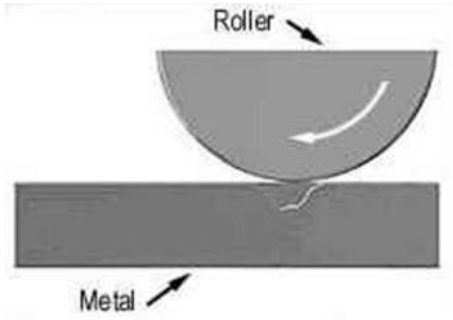
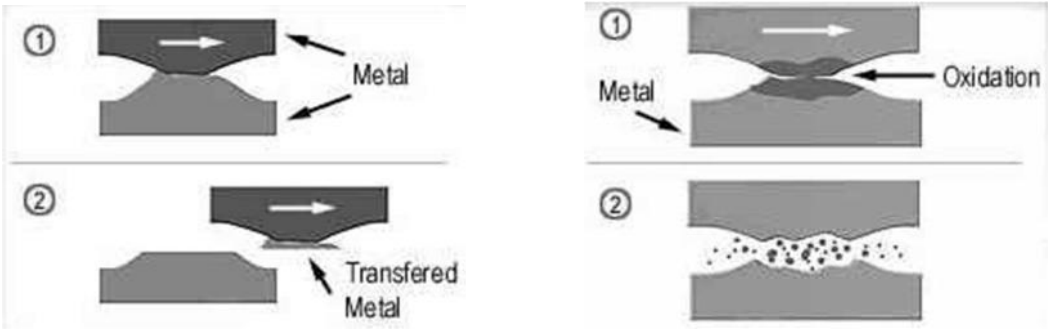


Fig. 2.5 Schematic representation of contact fatigue

2.3.1.5 Adhesive wear

This type of wear occurs due to sliding of two metallic components against each other under an applied load where no abrasives are present (Fig. 2.6(a)). A strong metallic bond forms between surface asperities of the contacting materials and hence the name 'adhesive' [10]. In case of stainless steel, there is a thin oxide layer on the surface, which prevents the formation of metallic bonding in between the asperities on the sliding surfaces. Hence, wear rates are low at low load.

This type of adhesive wear is known as mild wear or oxidative wear (Fig. 2.6(b)). When the load applied on the surface is high, metallic bond forms between the surface asperities and the resulting wear rates are high. This kind of wear is more prevalent where a lubricant cannot be used e.g. chain-link conveyer belts, fasteners and sliding components in a valve. For stainless steel, hardness affects adhesive wear resistance. For martensitic alloys, a minimum hardness of 53 HRC is required for excellent wear resistance. In austenitic stainless steel, the work hardened hardness is critical due to the presence of the alloying additions that increase the stability of oxide film. These factors increase the transition load required for severe corrosion to occur.



(a) (b)

Fig. 2.6 Schematic representation of (a) adhesive wear, (b) oxidative wear

The various types of wear, there symptoms and appearance of the worn out surfaces are given below.

Table 2.1 various types of wear, their symptoms & appearance [6].

TYPES OF WEAR	SYMPTOMS	APPEARANCE OF THE WORN OUT SURFACE
Abrasive	Presence of clean furrows cut out by abrasive particles	Grooves
Adhesive	Metal transfer is a prime symptom	Seizure ,catering rough and torn out surfaces
Erosion	***Presence of abrasives in the fast moving fluid and short abrasion furrows***	***Waves and troughs***
Corrosion	Presence of metal corrosion products	Rough pits or depressions
Impacts	Surface fatigue , small sub micron particles or formation of spalls	Fragmentation ,peeling and pitting
Fatigue	Presence of surface and sub surface cracks accompanied by pits and spalls	Sharp and angular edges around pits
Delamination	Presence of surface cracks parallel to the surface with semi dislodged or loose flakes	Loose , long and thin sheet like particles
Fretting	Production of voluminous amount of loose debris	Roughening , seizure and development of oxide ridges
Electric attack	Presence of micro craters or a track with evidence of smooth molten metal	Smooth holes

3. Experimental procedure

As received samples of high and low carbon steel bars were cut into 10 mm thickness samples. Around 10 samples (5 samples each from both the samples) were cut with the electric cutting machine. Water was provided frequently while cutting in order to prevent it from over burning as over burnt steel may make the heat treatment ineffective as grain refinement & other mechanical property might not improve albeit of performing any kind of heat treatment for any number of times. Electric cutting machine has a disc shaped sic plate which rotates at high speed to cut through the body of the bar. Precaution should be taken in order to get accurate measurement as high speed may displace the bar quite a bit; hence the samples may not be flat as well as might not be usable. Safety while performing cutting is vital as burnt metal particles may come into your eyes. Figure below shows the abrasive cutting machine.

Fig. 3.1 abrasive cutting machine

Then the samples were taken for different kinds of heat treatment operation. It was decided that 5 different kinds of heat treatment operation were to be adopted namely: - (1) Annealing

(2) Normalizing

(3) Oil quenching

(4) Water quenching

(5) Water delay quenching.

The samples were tied with steel wires having their top portion a bit curvilinear (umbrella stick shaped) in order to easy removal of samples from furnace after heat treatment as after heating to high temperature you never expect your hand to do the removal operation. Then the tied samples were placed inside a rectangular steel box fraught with charcoal. Charcoal protects the samples from oxidation as steel samples are vulnerable to oxidation at such high temperature. Carburizing is neglected at this temperature as holding time is less for diffusion to occur effectively on the surface. But in reality a bit of carburization might occur over the surface.

Then the samples with their designation (as after removal there won't be any confusion) were place inside a ceramic lined rectangular heating furnace of maximum heating capacity 1500^0 C.

The temperature was set to 960^0C. Actually it was decided to adopt a less temperature than this but the furnace had certain fluctuations and to avoid any possible inter-critical range austenitization, it was set at 960^0 C. Even though full annealing range for high carbon steel is way less than what we have adopted, it was decided to study the effect of same austenitizing temperature affect also. A rate of heating of 15^0 C/min was set.

After the furnace reached that temperature 1 hour holding was done at that temperature. Then the furnace was opened after making it switched off. To be annealed samples were put as it is inside it so as to have furnace cooling i.e. slow cooling. To be normalized samples were put in air. For water quenching, samples were put in water. For oil quenching, samples were put in oil. For

delay quenching, the sample was kept 30 seconds in the air before quenching in the water. Figure below shows the rectangular ceramic lined furnace in which heat treatment was done.

Fig. 3.2 Heat treatment furnace

After that the samples were taken for grinding and polishing. First the samples were grinded in a grinder in order to make the surface flat as well as to make it eligible for polishing. Then the samples were polished by 1/0, 2/0. 3/0, 4/0 emery papers before these were being taken for hardness measurement.

Vickers hardness as well as micro hardness was taken but accuracy of micro hardness was quite good to be considered. The model of the instrument used for finding out the micro hardness was LECO-LV700. Hardness of all the samples were measured in Vickers scale under a load of 50gf and dwell time of 15sec & noted down. The Vickers hardness of the samples was compared by plotting a graph between the hardness values and respective heat treatment performed.

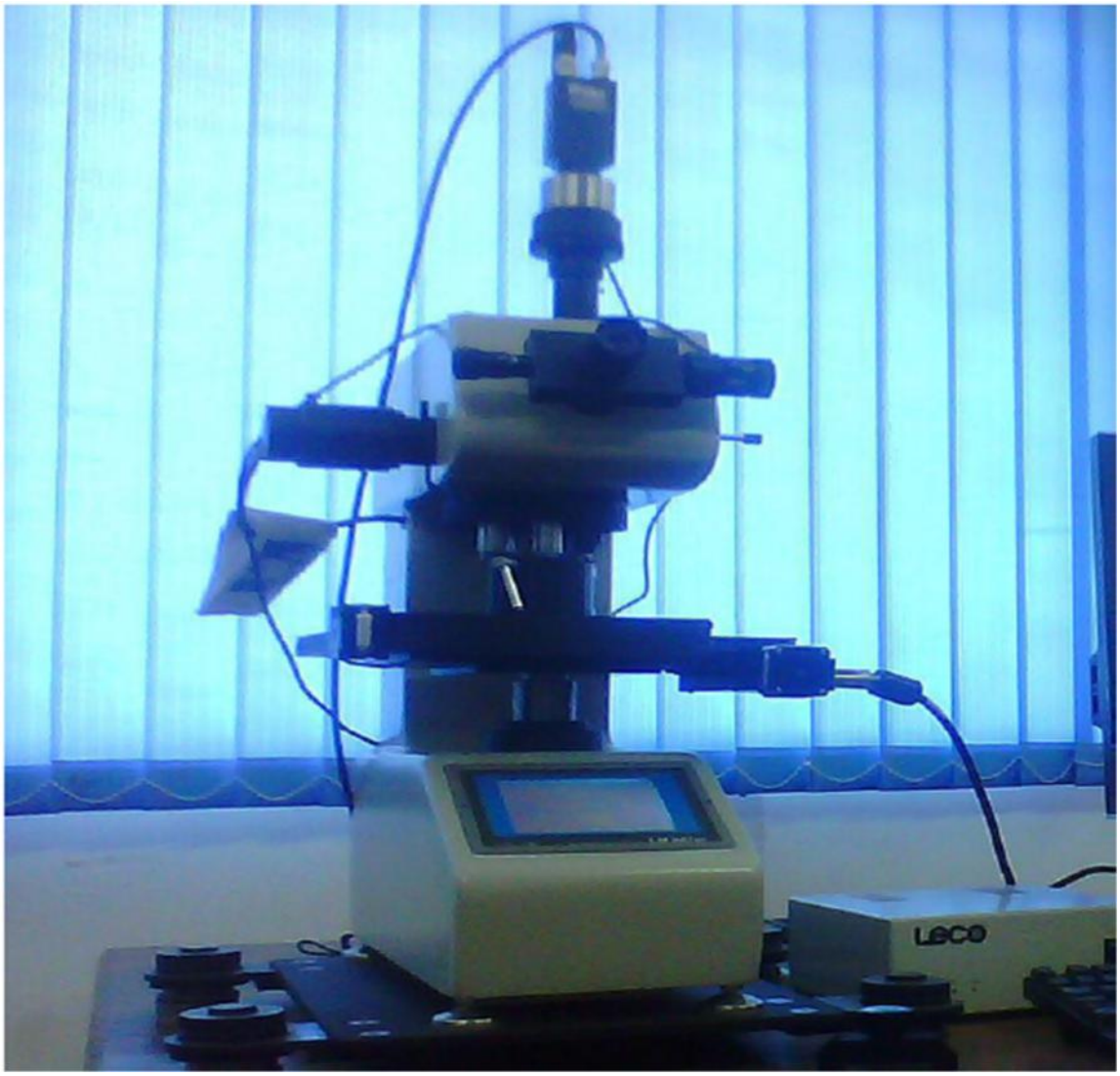


Fig.3.3 Micro Hardness Testing Machine

Then the samples were taken for cloth and diamond polishing. After fine polishing the etching of samples were done using Nital (98% ethyl alcohol& 2% HNO_3). Then the samples were taken for microstructural observation through high resolution optical microscopy. Microstructures were taken at 500X.

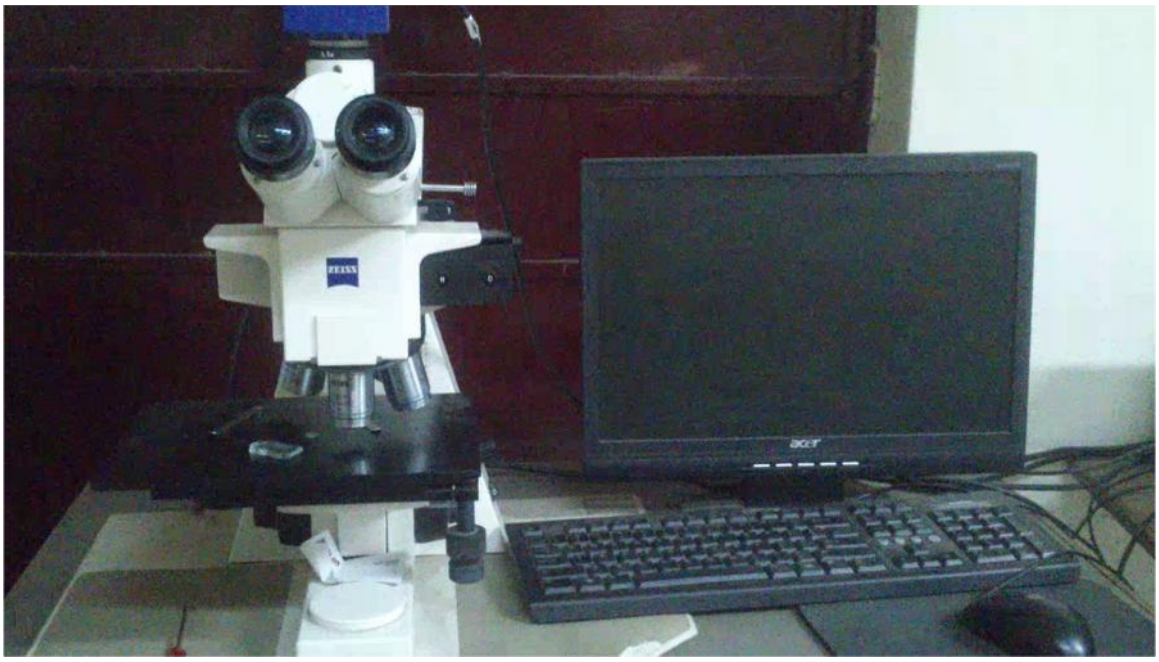


Fig. 3.4 High resolution optical microscope

Then the wear testing of all the samples was carried out. Wear testing in terms of sliding wear resistance of all the samples was evaluated using a ball on disc type wear testing instrument (DUCOM TR-208-M1) having a diamond indenter. Tests were carried out with an applied load of 2kg, 2 mm wear track diameter, 20 rpm rotating speed and 15 min time for the wear test. The results for the wear depth were obtained and the sliding distances were calculated by using the values of the wear depth and the process parameters. Graphs were plotted between the wear depth and sliding distance for different heat treatment operations as well as for different carbon content samples having same heat treated. These graphs were analyzed.

Fig.3.5 Wear testing machine

Finally the wear surfaces were taken for SEM analysis.The instrument model used for the SEM analysis was **JEOL JSM-6480LV**.A potential of 20KV was used for the scanning electron microscope and the magnification used for the samples were 30X & 150X respectively.The SEM images obtained for the wear surfaces of different samples were analyzed.

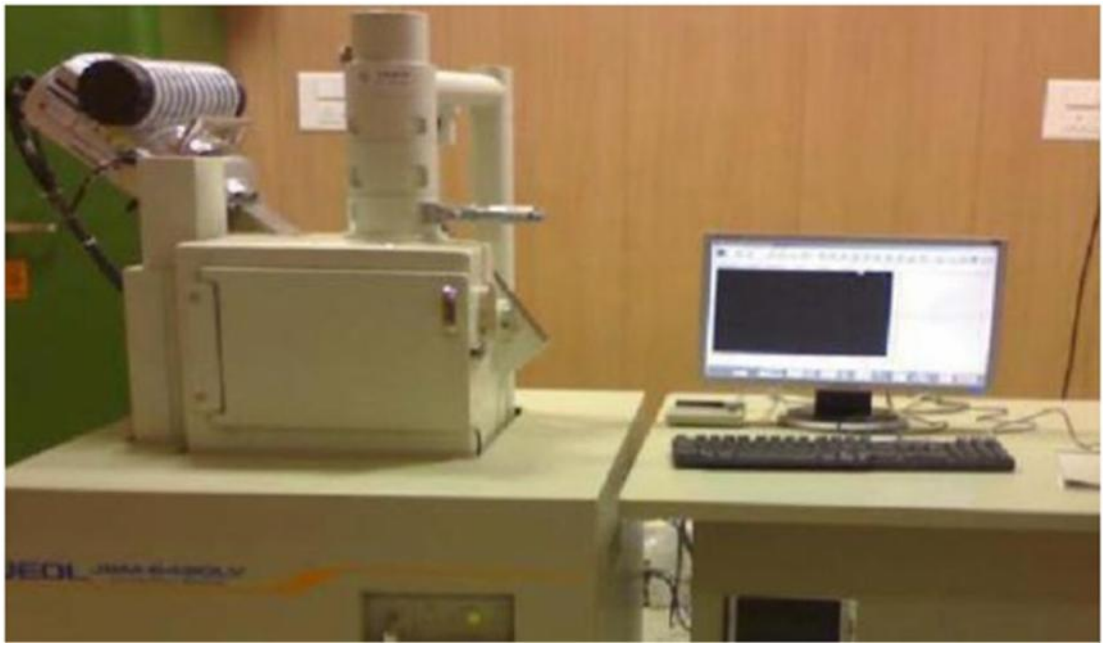


Fig.3.6 JEOL JSM-6480LV scanning electron microscope

4. Results and discussions

4.1 Hardness measurement

During micro hardness testing average of five individual reading on a particular sample was taken and reported in Table 1.

Table 4.1 Hardness values of samples after different heat treatment

Heat treatment processes	Hardness values(VHN)	
	Low carbon steel samples	High carbon steel samples
Annealed	207.03	283.20
Normalized	270.06	678.50
Water delay quenched	735.66	796.46
Oil quenched	723.76	786.16
Water quenched	763.03	812.96

To get a graphical easy understanding of the same bar chart of hardness values are shown in Fig. 4.1

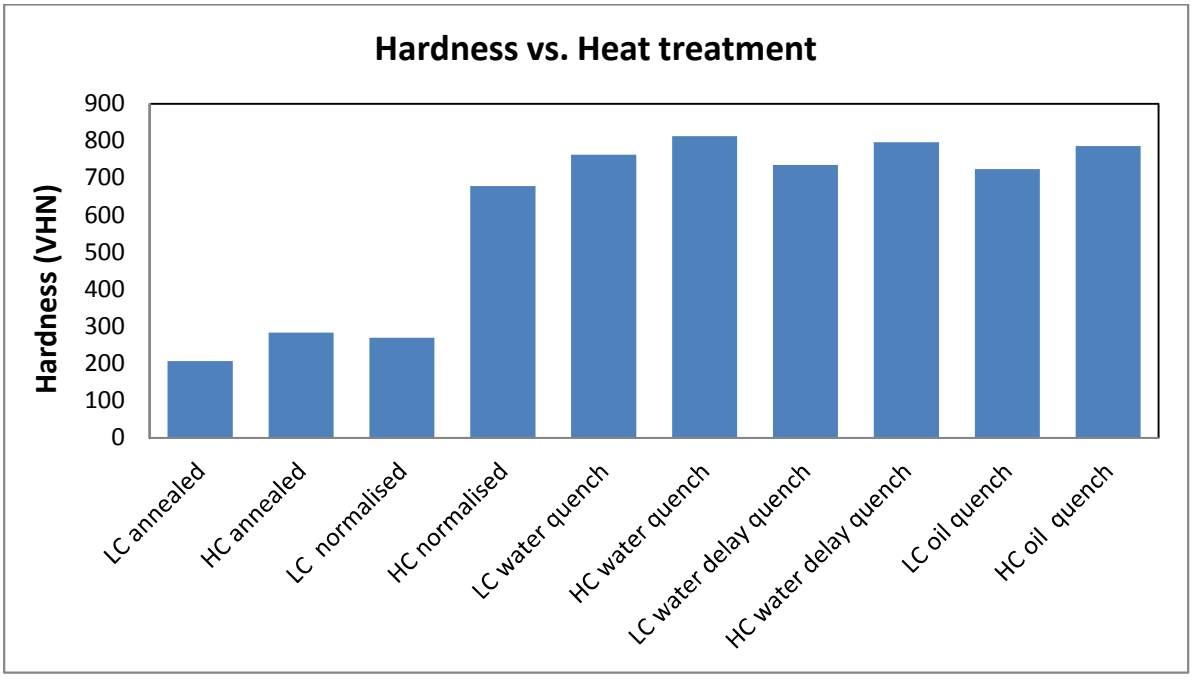


Fig 4.1 variation of hardness with carbon content and heat treatment

The graph shows that high carbon steel samples have higher hardness values as compared to the low carbon steel samples. Annealing and normalized high carbon steel samples have higher hardness compared to its low carbon counterpart. This is because high carbon steel samples have higher cementite phase as compared to its low carbon counterpart. High carbon quenched samples have higher hardness than its low carbon counterpart because super saturation increases with increase in carbon content which has a vital role in significant difference in hardness.

The order of hardness values of the different heat treated samples is as follows:

Annealed < normalized < oil quenched < water delay quenched < water quenched

Normalized sample has higher hardness than that of annealed sample because normalizing involves higher under cooling resulting in finer structure than that of annealed structure. Thus finer structure imparts higher hardness. Secondly, normalizing allows lesser time for proeutectoid phase (ferrite or cementite) formation; consequently more amount of pearlite is formed which imparts higher hardness.

Quenched samples have higher hardness than normalized samples due to formation of hard martensite. Water being more severe quenching medium than oil, hence, water quenched samples have higher hardness than oil quenched samples as faster cooling rate (water) generates finer martensite than slow cooling rate (oil). Again, faster the cooling rate there will be less chance of formation of pearlite or bainite which has less hardness as compared to martensite.

Water delay quenched samples have higher hardness than oil quenched samples as per data obtained. The reason might be the formation of less amount of martainsite in oil quenched samples as compared to delay quenched samples.

4.2 Microstructure

Optical microscopies of some samples are given below.

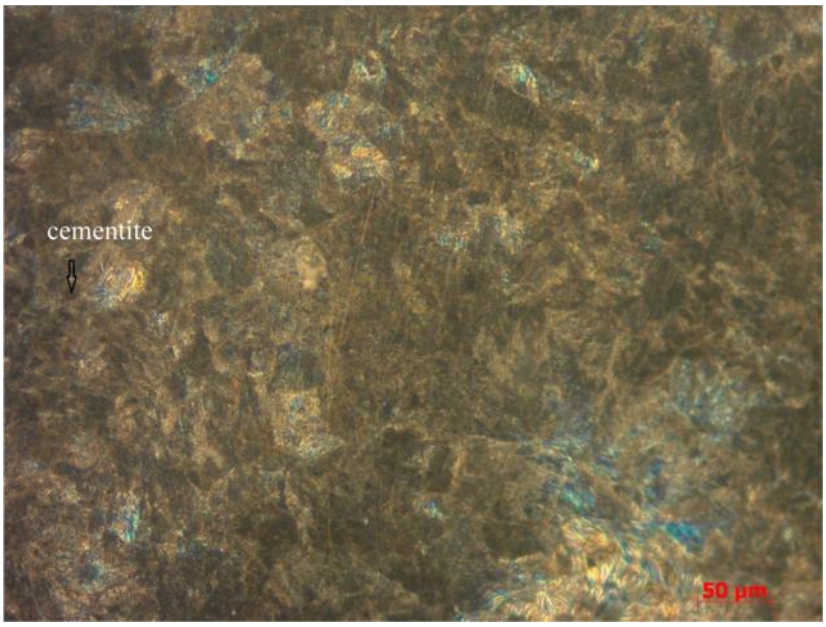


Fig 4.2 High carbon annealed sample at 200X

As indicated in the figure black phases are cementite which appears as networks throughout the surface because of high temperature used instead of full annealing temperature range for high carbon steels. Other phases are not visible but the colored marks might be due to burning.

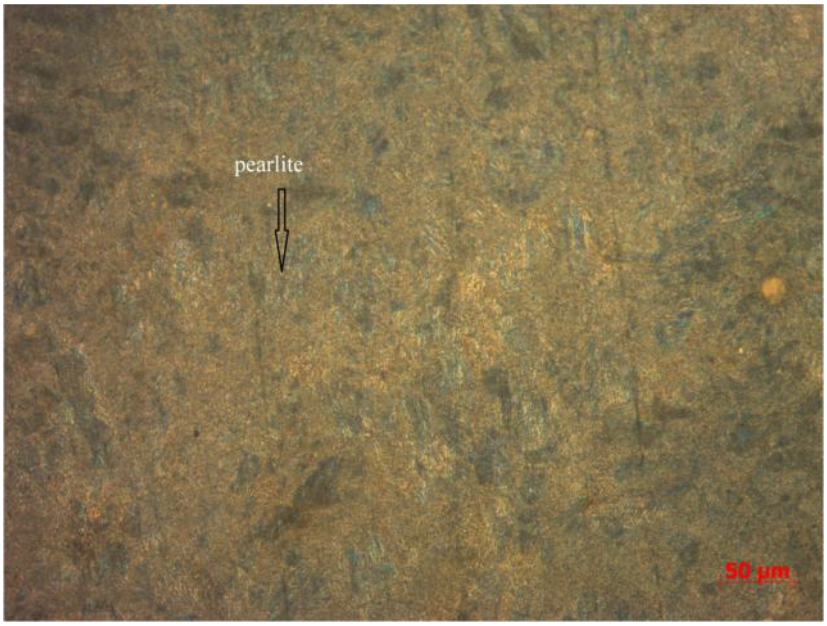


Fig 4.3 low carbon annealed sample at 200X

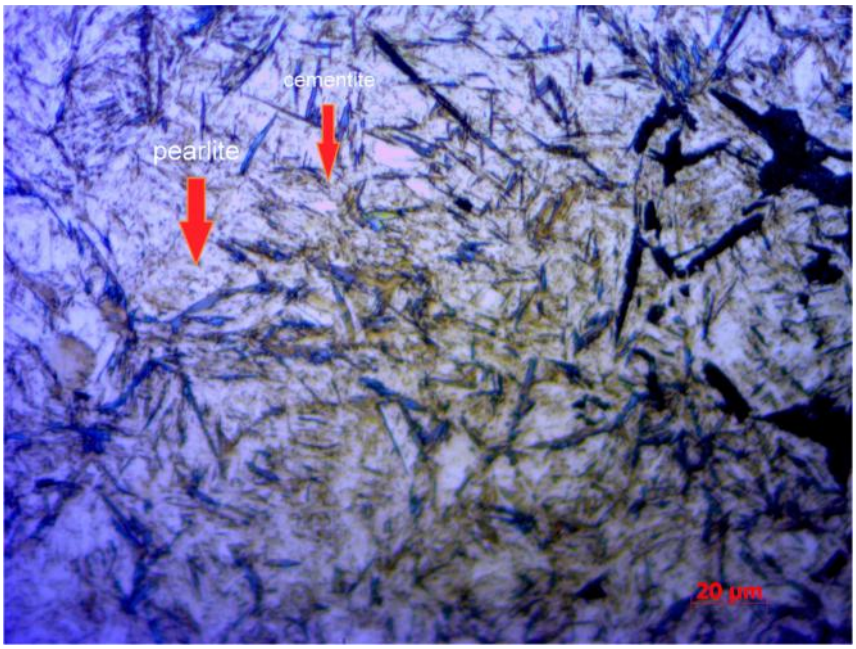


Fig 4.4 High carbon normalized sample at 500X

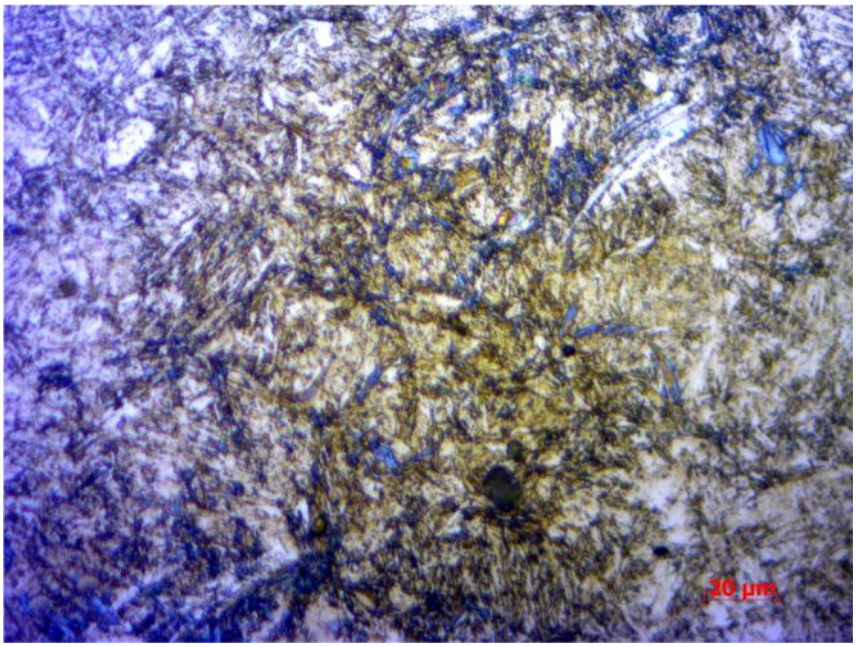


Fig 4.5 High carbon water quenched sample at 500X

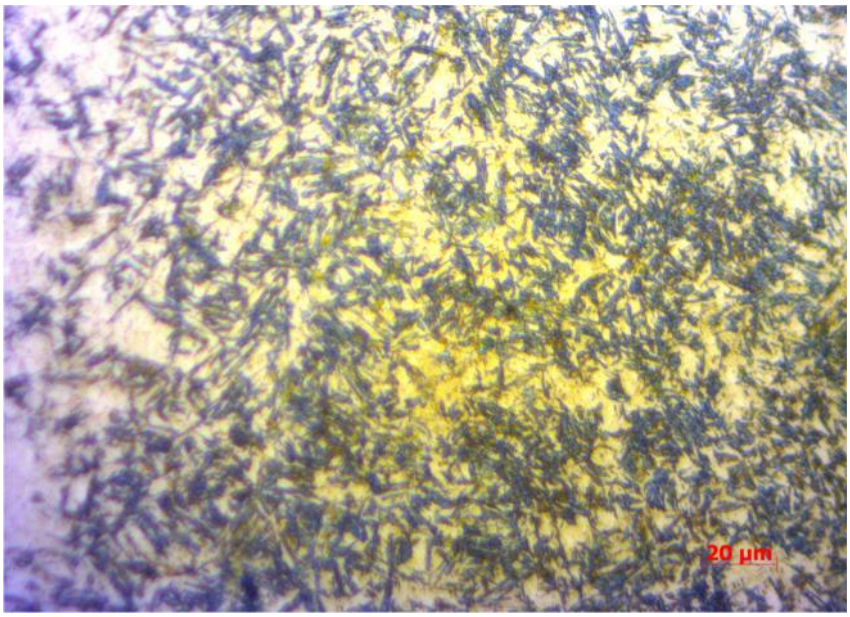
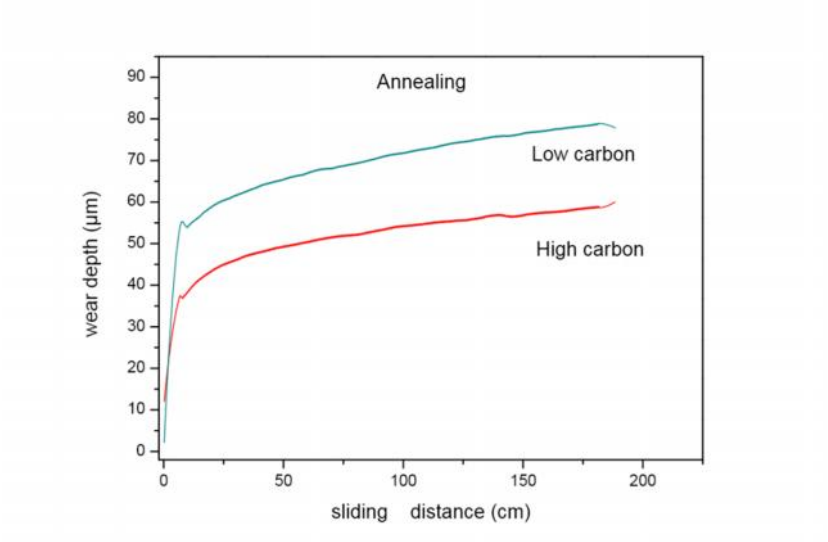


Fig 4.6 Low carbon water quenched sample at 500X

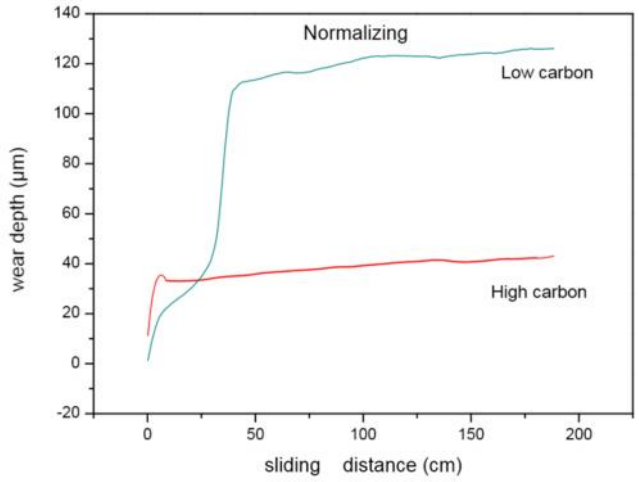
In general all the low and high carbon quenched (water and oil) samples show presence of martensite and for obvious reason the amount is negligible in low carbon steel.

4.3 Wear Behavior

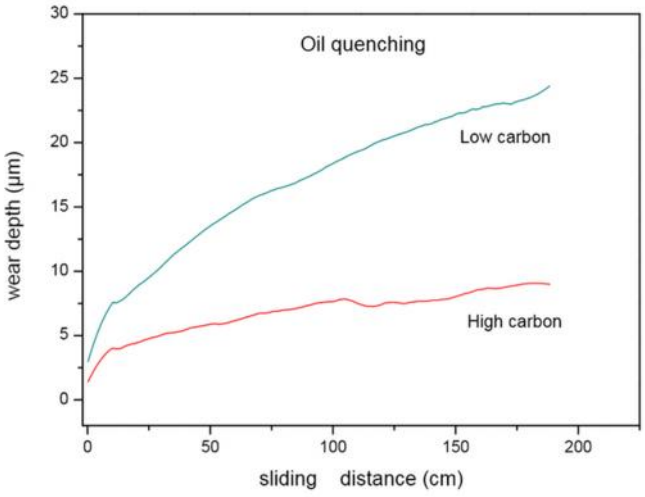
The data collected from wear test of all the samples were converted to graphs between the wear depth and the sliding distance. The plots related to wear are shown below:



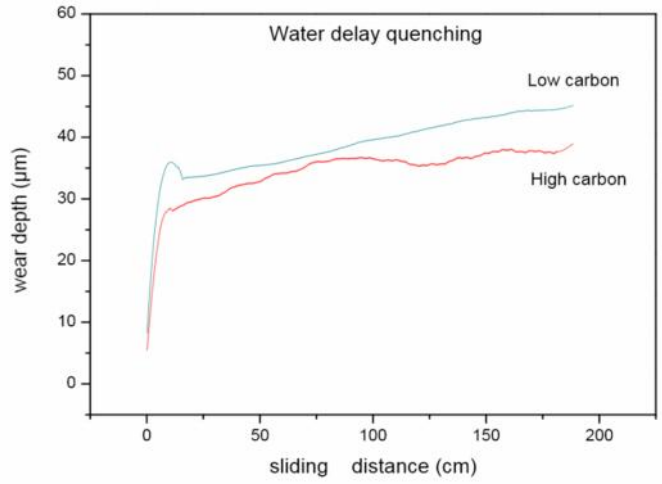
(a)


Normalizing
Low carbon
High carbon
wear depth (μm)
sliding distance (cm)
140
120
100
80
60
40
20
0
-20
0
50
100
150
200

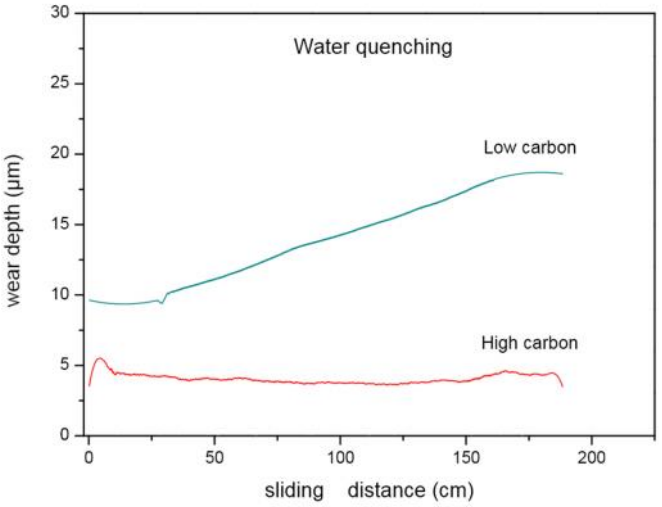
(b)


Oil quenching
Low carbon
High carbon
wear depth (μm)
sliding distance (cm)
30
25
20
15
10
5
0
0
50
100
150
200

(c)



(d)

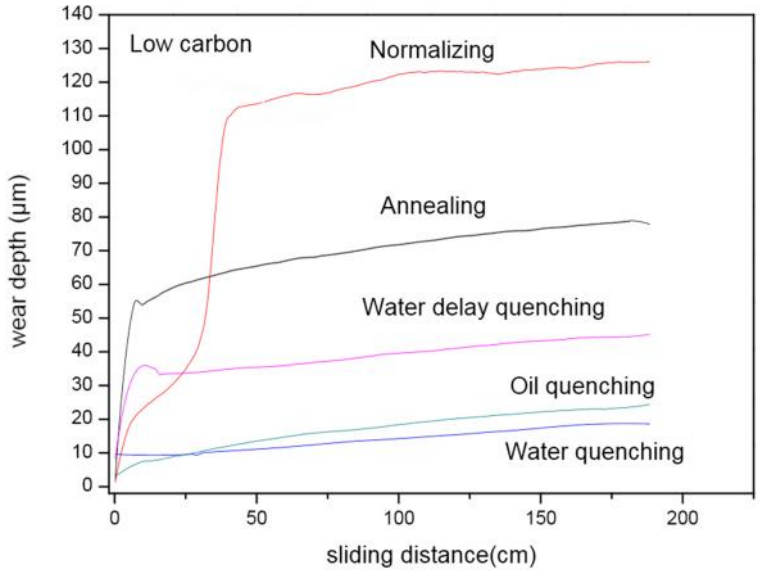


(e)

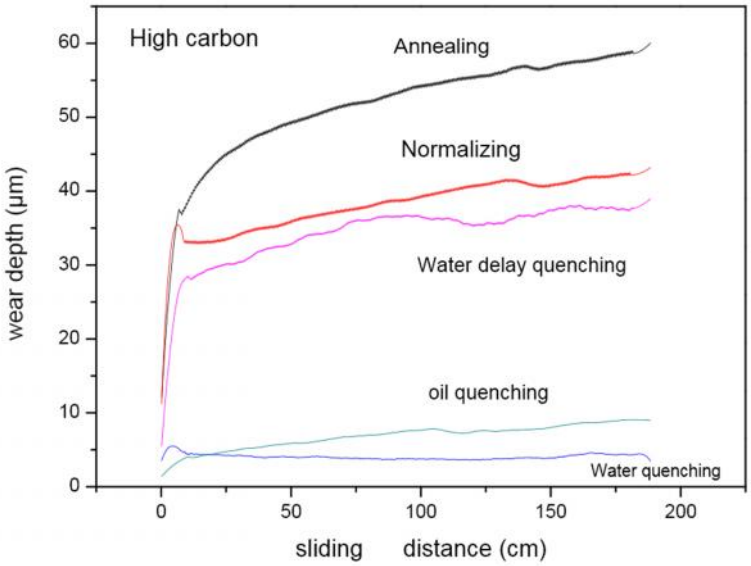
Fig. 4.7 (a) – (e): Variation of wear depth with sliding distance for low as well as high carbon steels at different heat treatment operations

The above graphs show that high carbon steels are more wear resistant than low carbon steels in all heat treatment operations. As hardness and wear resistance are synonymous in general, so, steel samples having higher hardness (i.e. high carbon steel samples) have high wear resistant as compared to steel samples having lower hardness.

Figures below show the variation of wear depth vs. sliding distance of same samples but differently heat treated.



(f)



(g)

Fig 4.8 (f) & (g) graph showing variation of wear depth vs. sliding distance at different heat treatment operations.

The carbon content apparently had little effect upon the wear of annealed steels. Rather surprisingly, the wear of the low-carbon normalized steel was greater than that of the annealed steel ofsimilar carbon content, but with increasing carbon content the wear rate of the normalized steel decreased rapidly, approaching, in thehigh-carbon range, the relatively high wear resistance of the delay hardened steel. Generally speaking, it is true that the harder the material, the better is its wear resistance with the exception of the low-carbon normalized steel sample which showed a higher wear resistance than the annealed steels. Low carbon annealed sample shows the softest condition in the entire study as per the hardness value but as per the wear test is different due to excessive ductility of the sample. High ductility shows pronounced adhesive wear mechanism, i.e. the wear debris may re-weld on the track again leading to low wear depth result. Thus it shows better wear resistant than the normalized sample in the graph.

From the study (data and the microstructures), it is evident that a martensitic structure is the most favorable for resisting wear. Although both the annealed and the normalized steel in the high-carbon range are relatively soft as compared with the hardened steels, their resistance to wear varies widely. The normalized high-carbon steel shows a resistance to wear almost as great as that of the delay hardened high-carbon steels, while the annealed high carbon steel shows a relatively poor resistance to wear.

The micro structure of these normalized and annealed high-carbon steel vary so much. They might be divided into two classes. The micro structure of the normalized steel is of lamellar pearlite; whereas that of the annealed steel is mostly spheroidized cementite and ferrite. This spheroidization was the result of the relatively slow cooling undergone by the steels during the annealingtreatment. According to Lehman [7], lamellar pearlite is quite resistant to wear as he found in making wear tests on cast ironthat the main factor which governed the resistance to wear of cast iron was the percentage of pearlite.

Evidently the presence of either free ferrite or free cementite (as spheroids) is detrimental to the wear resistance of normalized carbon steel. That free ferrite is distinctly harmful in low-carbon steels, all of which exhibited low resistance to wear [8].

As previously mentioned, the normalized low-carbon steel showed slightly less resistance to wear as the same steel when annealed. The pearlite in the annealed steels was surrounded by

cementite networks. The normalized steel did not show this feature in itsmicrostructure. These networks, being rather continuous and much stronger than the surrounding ferrite, are undoubtedly responsible for the wear resistance of the low-carbon annealed steelbeing greater than that of the same steel when normalized.

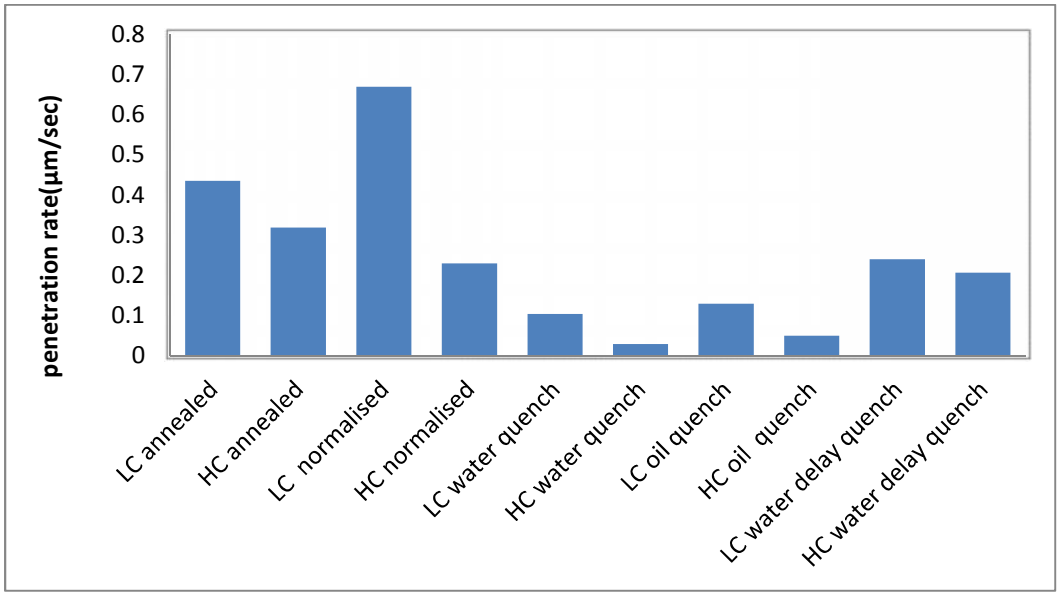


Fig.4.9 graph showing maximum penetration rate vs. heat treatment

During the wear study of maximum depth of penetration, penetration rate was calculated (dept/time) and is shown in Fig. 4.9. This also gives a comprehensive idea of the wear study and shows similar trend as discussed from earlier figures. As explained above high carbon water quenched sample shows least penetration rate & low carbon normalized steel shows highest penetration rate.

4.4 Scanning Electron Microscopy

The worn surfaces obtained after wear tests were studied under SEM and shown below.

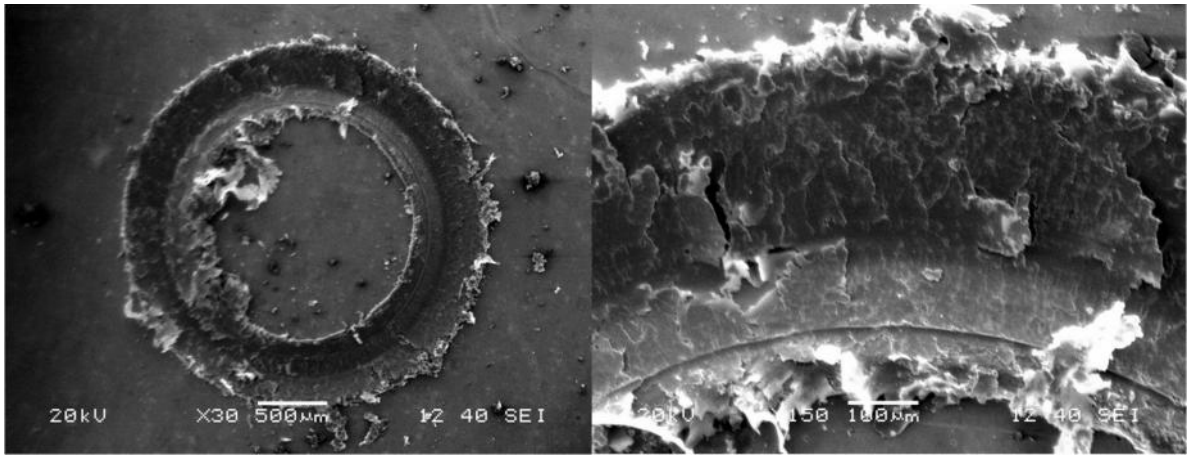


Fig.4.10 Low carbon annealed steel at 30X Fig.4.11 Low carbon annealed steel at 150X

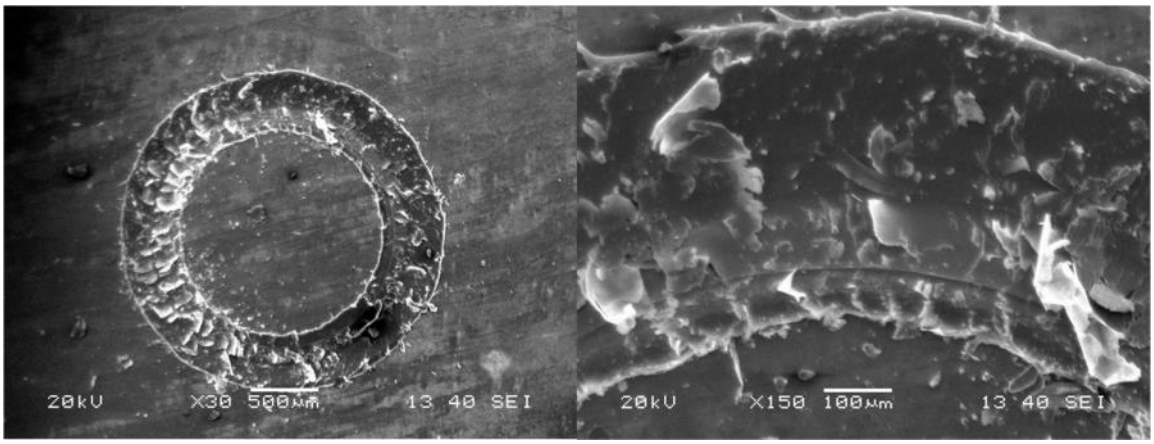


Fig.4.12 High carbon annealed steel at 30X Fig.4.13 High carbon annealed steel at 150X

Above SEM images demonstrate clearly that high carbon annealed steel samples have higher wear resistance than low carbon steel sample as evident from the width of track. In case of low carbon it's more irregular and distorted and the width of track is more. Hence more material has lost in case of low carbon steel samples.

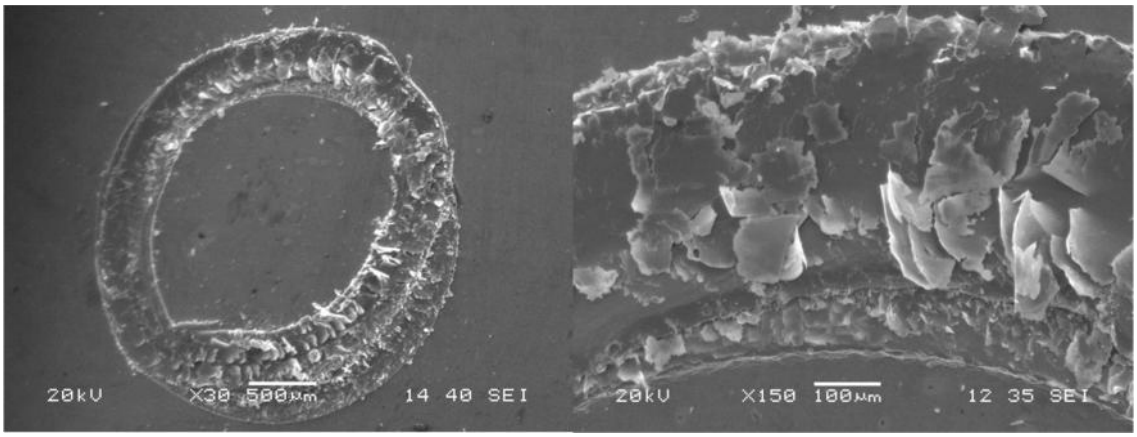


Fig.4.14 Low carbon normalized steel at 30X Fig.4.15 Low carbon normalized steel at 150X

As explained in the wear graphs low carbon normalized steel samples have least resistant to wear as evident from the width and distortion of wear track.

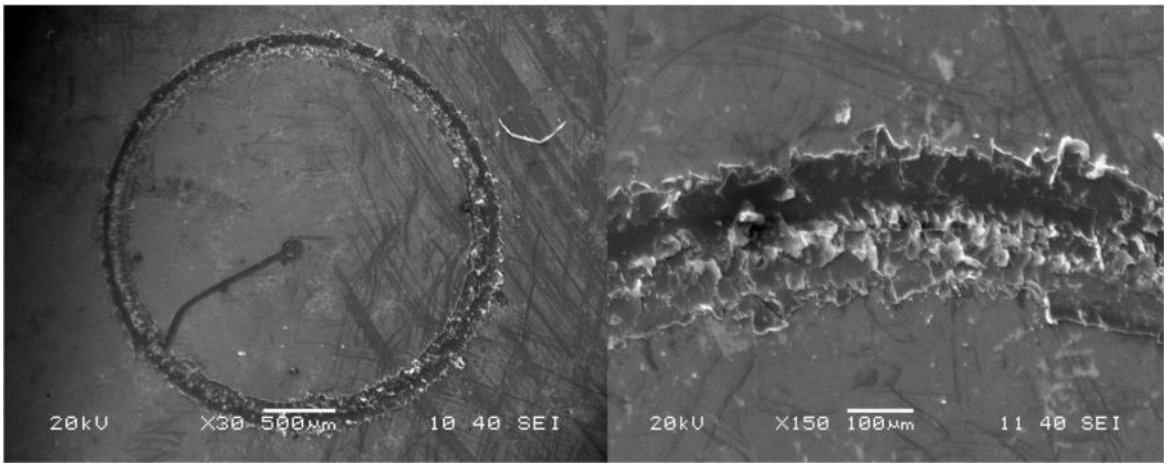


Fig.4.16 High carbon normalized steel at 30X Fig.4.17 High carbon normalized steel at 150X

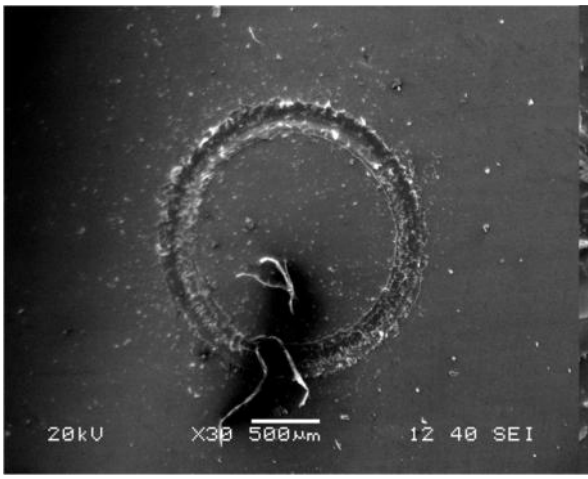


Fig.4.18 Low carbon water quenched steel at 30X

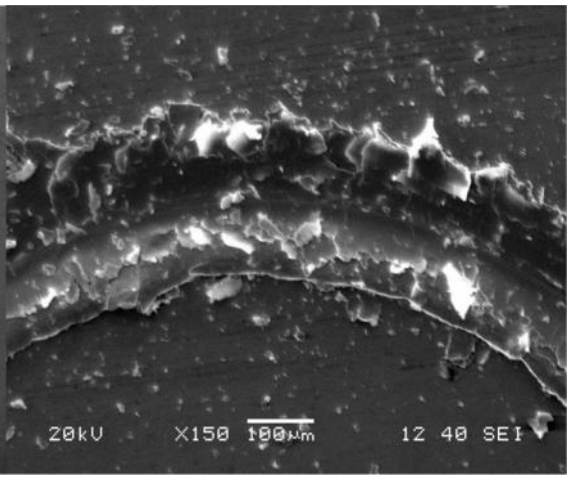


Fig.4.19 Low carbon water quenched steel at 150X

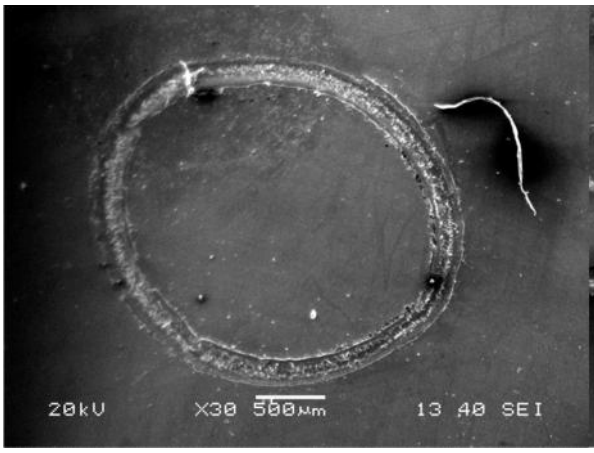


Fig.4.20 High carbon water quenched steel at 30X

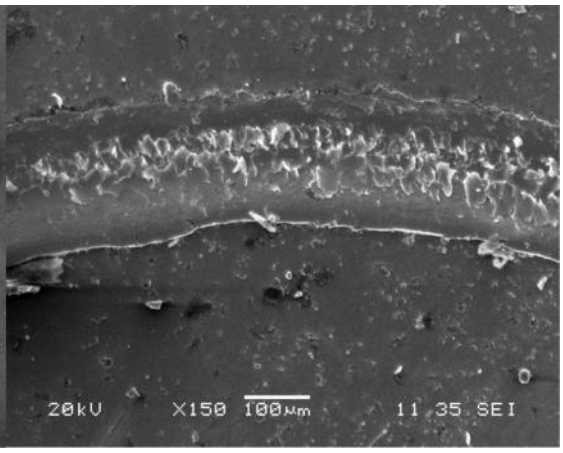


Fig. 4.21 High carbon water quenched steel at 150X

From the wear images above it can be seen that there is more rubbing activity and depth of penetration in case of low carbon quenched steel. Hence abrasive wear is prominent here as compared to high carbon quenched steel.

High carbon normalized and in general all the quenched samples show abrasive wear mechanism as in the wear track we can find more scratching and rubbing instead of re-welding.

5. Conclusion

The resistance to wear of carbon steels was studied by means of the diamond indenter on a ball-on-plate wear testing machine in which the material is subjected to combined rolling and sliding friction underpressures. Annealed carbon steels gave relatively poor wear-resisting qualities for all carbon contents. Normalized steel showed low wear resistance in the low-carbon range, but had greatly improved wear resistance in the high-carbon range. Low carbon annealed sample shows the softest condition in the entire study as per the hardness value but as per the wear test is different due to excessive ductility of the sample. High ductility shows pronounced adhesive wear mechanism, i.e. the wear debris may re-weld on the track again leading to low wear depth result. Thus it shows better wear resistant than the normalized sample. The hardened steel showed low wear-resistance in the lowest carbon ranges, but as the carbon content increased the wear resistance increased. The water delay quenched steel showed lesser wear resistance as compared to oil quenched samples though the hardness of former is more than the latter. A martensitic micro structurewas the most favorable for resisting wear of the type studied. Properly normalized high-carbon steels, which showed a structure of lamellar pearlite, had almost as good wear resistance as the delay hardened steels. Annealed high-carbon steels, if shows a micro structure predominately spheroidized cementite, has relatively poor resistance to wear. Apparently free ferrite or free cementites (as spheroids) are detrimental to the resistance to wear.

6. References

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